Dosimetry Comparison of Gamma Knife and External Beam Radiation Therapy on Brain Tumors

Research Thesis

Presented in partial fulfillment of the requirements for graduation *with research distinction* in the undergraduate colleges of The Ohio State University

by

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I. Abstract

The practice of stereotactic radiosurgery (SRS) dates back to 1951 with Swedish Neurosurgeon Lars Leksell. However, in an age where cancer diagnosis and treatment has become so prevalent for our society, results from clinical techniques such as SRS have become more significant. The two most commonly used methods for performing SRS are Gamma Knife (GK) and External Beam Radiotherapy/Linear Accelerator (LINAC). While the two methods have been clinically performed independently, very few attempts to compare the applied treatment plans have been made. This comparison involves evaluating the different methodologies with identical patients, using identical imaging, critical structures, and target volumes. This is the focus and goal of the study. The process of obtaining the results involves first yielding simulated treatment plans from GK and LINAC methods independently. Identical patients' CT image are used and dosages are normalized between the methodologies, for the percent prescription isodoses for GK and LINAC differs from one another. From there, the LINAC data is sent to the GK system and a side-by-side comparison can be made. Using the results stemming from this project, radiation oncologists and other cancer health professionals can more confidently make the decision of what method of SRS to deliver to the patient while maximizing the cancer tissue treated and doing the least harm to the healthy tissue surrounding the malignancy. The implications of this research should lead to continued comparative examination of these SRS methodologies and their effectiveness to treat the patients' target volumes, leading to more benefits reared by patients.

II. Introduction

A. Background

In 1951, in an attempt to treat small lesions in the brain, Swedish neurosurgeon Lars Leksell introduced the concept of stereotactic radiosurgery, abbreviated SRS (Gianolini, 2006). This concept involved applying an external beam of radiation to a volume of the cranium, where delivery was administered, in a stereotactic manner, through multiple entry points called arcs. The term "surgery" was given to this procedure because the intent is to damage certain cells within a set volume, even though it did not involve the typical instruments associated with a surgical procedure. Currently, two mainstream methodologies for delivering SRS treatment are Gamma Knife (GK) and linear accelerator (LINAC), with both similarities and differences existing between them.

Figure 1 (left):

Gamma Knife machine with patient in supine position

Gamma Knife radiation treatment has been in use since the introduction of its prototype in the late 1960s. GK systems are cobalt 60 (Co-60) systems, meaning that cobalt is used as the source of the gamma rays which treat the patient (Columbia, 2017). Co-60 is a radioactive source with a 5.27-year half-life. The beam energy from Co-60 is dichromatic beams of 1.17 and 1.33 MeV, resulting in an average beam energy of 1.25 MeV. The machine has 192 Co-60 sources that are arranged in a special format to converge the radiation beams from these 192 or some of the 192 sources to a focus spot to deliver the treatment, and tumors in a patient's brain are moved to the focus for treatment (University of Arkansas, 2017).

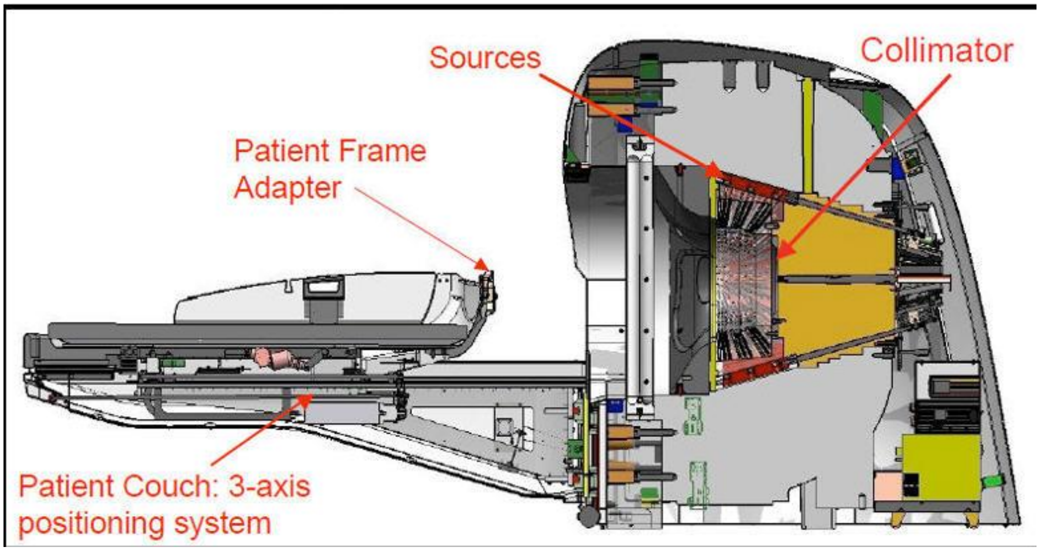


Figure 2:

This diagram shows a schematic view of the Gamma Knife machine and the essential elements of the machine including the sources, collimator, and couch.

In current daily routine Gamma Knife procedures, the GK plan uses TMR 10 for dose calculation, which consider the tissues being homogeneous and bone or soft tissue are treated as water. However, in general, LINAC treatment plans have taken into account the tissue inhomogeneity, for example bone is considered as bone and air is treated as air. To do a fair comparison, in GK treatment plans, we also must consider the tissue inhomogeneity correction. To do this, we first generated a TMR 10 treatment plan, then recomputed the dose with the Convolution method to consider the inhomogeneity correction. The Convolution plan will be used for the comparison between GK and LINAC, but comparison between TMR 10 and Convolution will also be made.

Figure 3 (left):

Linear Accelerator machine

The first concepts of linear accelerators were introduced in the 1920s but was not used as a medical treatment method until the 1950s. The methodology uses microwave energy to accelerate electrons and focus them to a metal target. This action generates high energy X-ray beams with photon energies used for the treatment of the tumors (Gianolini, 2006). The use of a collimator is very important for this methodology, and the machine used in this study at The Ohio State University is equipped with a multileaf collimator (MLC). The MLCs allow for more precise treatment for irregular shaped tumors. A MLC system is composed of 120 pieces (60 pairs) of tungsten, and each is driven by a small motor that is controlled by computer to shape the format of beam to cover different shapes and sizes of tumors.

Figure 4:

Multi-Leaf Collimator (MLC) used for LINAC-based radiation therapy showing the tungsten pieces assembled in pairs and shaped to a desired form for a specific tumor

The LINAC X-ray beam used to treat the brain tumors is generally a 6 MeV beam. The energy spectrum ranges up to 6 Mega-Volts with the mean at about 2 MeV. Since the beam energy for LINAC is higher than Co-60 beams, radiation beams may penetrate deeper for LINAC beams than Co-60 beams, which may also have the potential to deposit more energy to normal tissues outside the tumors.

Similarities between the GK and LINAC methodologies can be found through the treatment procedures. Four characteristics that are common to almost all SRS treatments are fixation of a stereotactic frame, stereotactic imaging, planning using computer programs, and the execution of the radiosurgery itself. The implementation of a fixated stereotactic frame is important because it ensures immobilization of the skull while treatment is in progress. It is essential that mechanically, the radiation is hitting the same coordinates of the skull as the computer planned, otherwise more healthy tissue would receive the dose. To plan the radiation treatment, sufficient imaging must be produced. Imaging studies such as NMR, X-rays, and CTs are most commonly used. For this study, CT imaging was implemented after critical structures were marked and analyzed by a radiologist.

The planning of radiation treatment implements treatment planning software on computers, where location of treatment and prescription dose is calculated. While certain methodologies of SRS treatment may use different software, many of these dose-planning programs share many characteristics. The treatment plan consists of different measures and values including isodose curves, shots, and collimator size. An isodose line displays the points in tissues that get the same doses. For GK, a physician would prescribe a dose to a tumor at the 50% isodose line (for example 20 Gy), while for LINAC, the physician would prescribe the same dose (in this case, 20 Gy) but to the 90% or 100% isodose line. Shots and collimator sizes are related. Shots are a set of high focused, successive treatments in the brain. Multiple shots are used to cover the entire tumor, and 100% coverage is the goal for treatment. The shots can cover varying volumes, though, depending on the size of the collimator. In this study, the collimator sizes were 4 mm, 8 mm, and 16 mm. It is often most efficient to use larger shots when possible because the less shots, the less time required for treatment. Time of treatment is a factor to consider because the patient is constrained for that length of time.

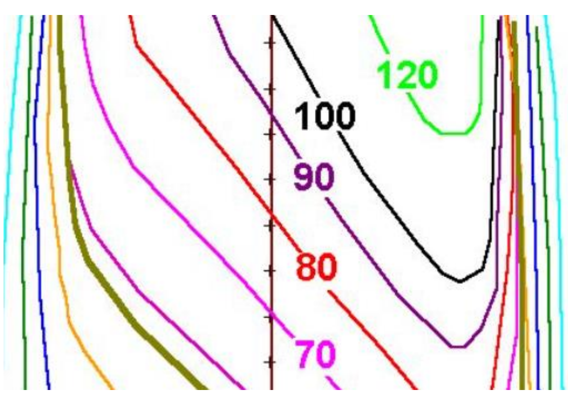


Figure 5 (left): Example of how isodose lines are displayed. Areas marked by the same isodose line will receive the same dose level during treatment.

When calculating the target volume for the plan, three target volumes are calculated. These volumes consist of gross target volume, clinical target volume, and plan target volume. Gross target volume, GTV, is the volume of the tumor itself, which no correction factor. Clinical target volume, CTV, has a volume greater than that of GTV because it includes extra volume for microscopic disease that could be surrounding the tumor. Plan target volume, PTV, is a volume greater than that of GTV and CTV, as it accounts for the uncertainty of skull movement during treatment. The added margin is called the setup margin. For GK treatment, the skull is completely immobilized and secured to the bed by use of a frame. Therefore, the GTV, CTV, and PTV should be the same. For LINAC, however, there is uncertainty in skull movement because a mask is used instead of a frame which is not used for immobilization, so the volume to be prescribed is the PTV, which indicates there is a possibility of more normal tissue to be irradiated. In this study, a comparison is made between the GTV of GK and LINAC so the volumes are identical and only the differences in the methodologies are compared.

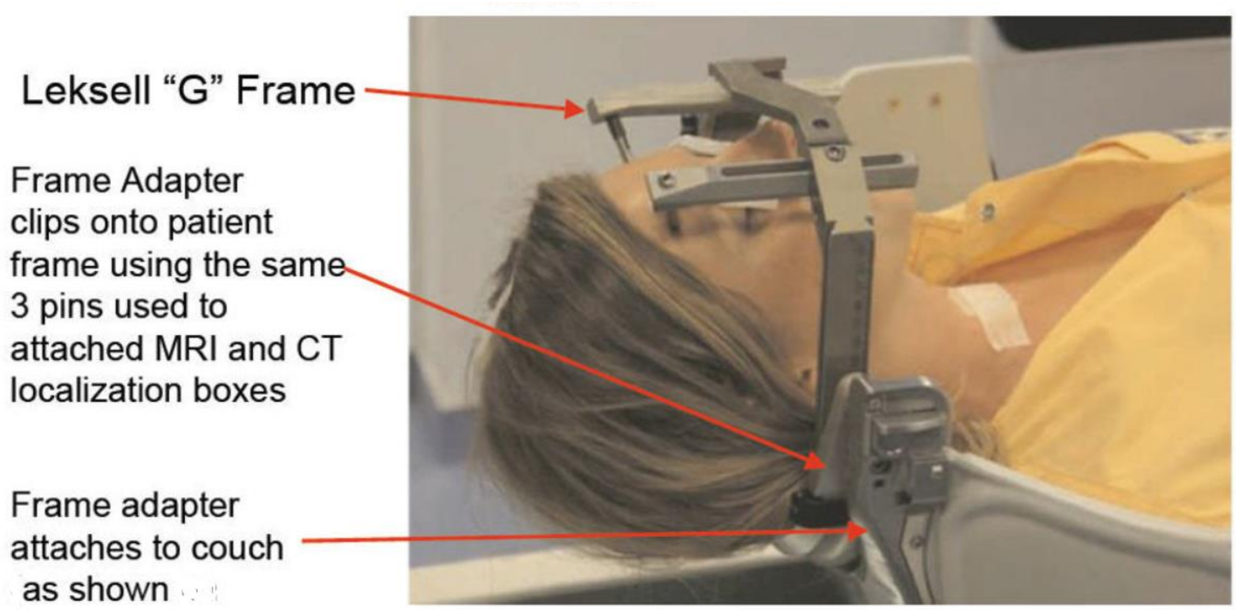


Figure 6:

Patient in head frame for Gamma Knife treatment. This frame creates immobilization of the patient’s head and allows for me accurate and precise treatment of the tumor

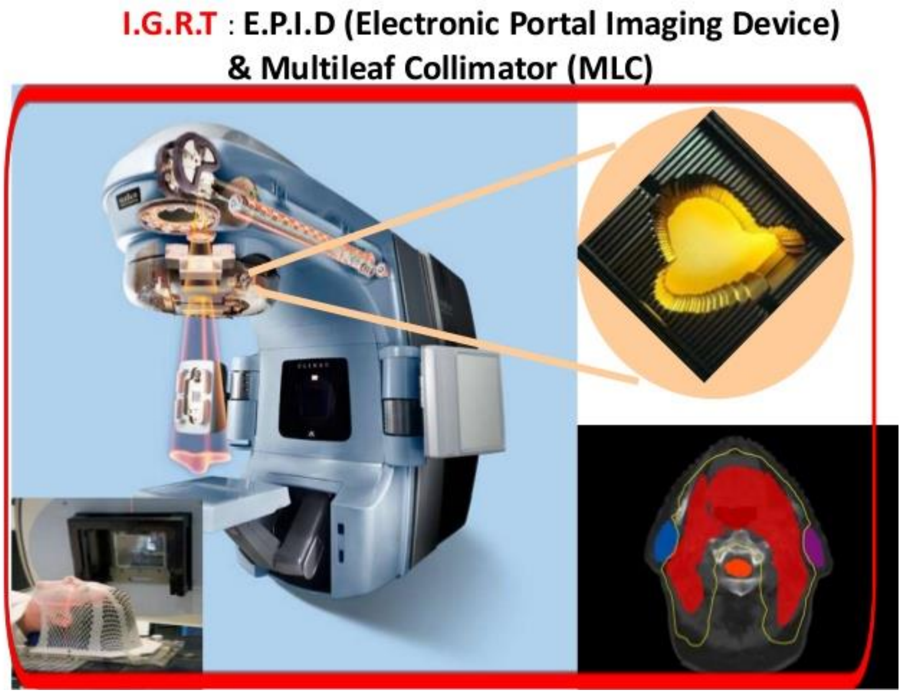


Figure 7:

Schematic Display of LINAC machine and MLC technology. Bottom left image shows the mask worn for treatment, which compares to the frame seen in previous figure

The purpose of using these methods of treatment is to damage and kill select cancer or tumor cells in the cranium. The direct effect is the ionizing radiation creating DNA strand damage, due to the sensitivity of the cell nucleus to the prescription dose of radiation. The cells end up dying in either an abortive phase of mitosis or through apoptosis, programmed cell death. The tumors themselves, clusters of cells with uncontrolled cell growth, can vary greatly in size or the rate at which they grow. There is also unequal sensitivity to radiation treatment among the tumor types, creating a need for unique treatment plans with varying target doses and volumes. The ionizing radiation that is being delivered is measured in Gray (Gy). Gray is the SI unit of radiation dose and is the amount of absorbed energy per unit mass of tissue. The planned dose statistics can be more easily analyzed using dose-volume histograms (DVHs), which displays the dose given over a given volume and how a dose gradient exist over the volume, to decrease the amount of radiation delivered to the surrounding healthy tissue.

B. Purpose

While GK and LINAC treatments have been clinically performed independently, very few attempts to compare the applied treatment plans have been made. In an attempt made possible by completing this experiment, treatment plans from both methodologies, GK and LINAC, were compared using identical patient imaging and target volumes. These plans were for treatment of individuals with single metastases of the brain. Three different tumor types were also studied, including metastatic tumors, pituitary tumors, and acoustic schwannomas. Results were analyzed in such a way that radiation dose prescription coverage of the malignancy and amount of the adjacent healthy tissue affected were compared side by side for these two methodologies. Maximizing the treatment coverage area and minimizing the amount of healthy tissue exposed to radiation leads to the most effective outcomes for cancer patients. The results of this study provided insight on which of the methodologies were more efficient on treating the malignancies and which should be used more frequently in the future, the goal of radiation oncology. Combining the results and evaluating the DVHs as larger groups can lead to conclusions about the effectiveness of each modality on treating target volumes such as brain tumors.

C. Significance

The results that have come from this study have significance not only in the area of radiation oncology but to the greater world of medicine and healthcare. According to the National Cancer Institute, cancer is one of the leading causes of death worldwide, with mortality rates being 207.9 per 100,000 men and 145.4 per 100,000 women. The diagnosis of cancer, a stressor in itself is also an elevated value, as around 40 percent of men and women will be diagnosed with cancer in their lifetime (NIH, 2016). The innovation of screening for cancer has decreased the mortality of the disease, and advancements in treatment such as radiation treatment has led to increased survival rates, emphasizing the significance of the research.

The approach taken in this study to compare the GK and LINAC treatments using identical patient imaging and target volumes is also one of innovation. Since all patient volumes, targets, and structures in general are identical, only the course of treatment is the variable, allowing a direct comparison to be made. At The Ohio State University, having certain technologies such as computer programs for both GK and LINAC treatment plans have enabled the communication of patient data from one system to another, allowing the comparison to be possible. By presenting this form of comparative study to the scientific and medical world, similar studies could be reproduced and created to gain more knowledge of which radiation treatment is more beneficial to cancer patients. In the end, the well-being of the patients is of the upmost importance and is the reason behind this research.

III. Methods

In figure 8 (see below), a diagram shows the general steps taken to obtain results and analyze such results in this study.

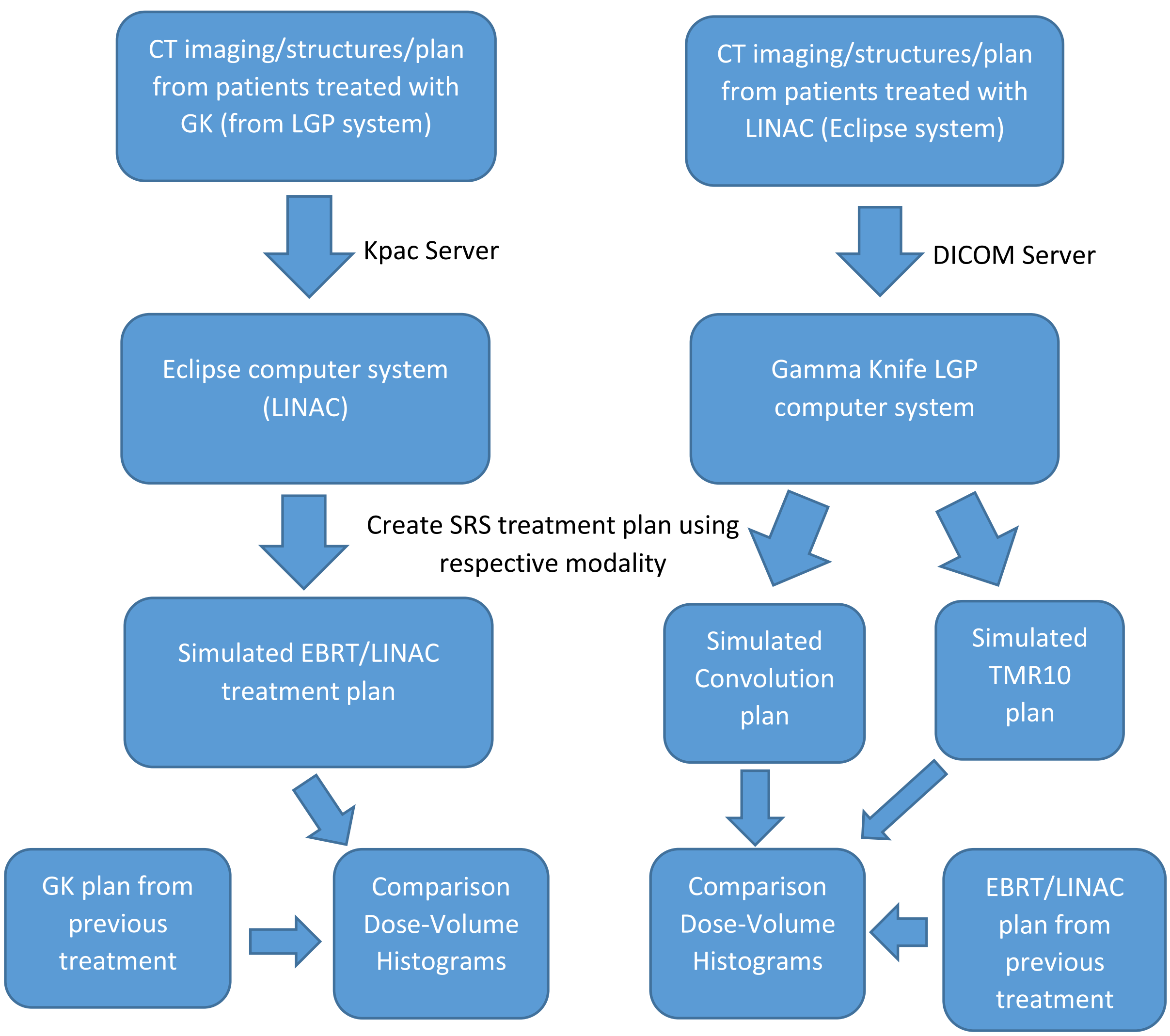


Figure 8: Procedure Flowchart/Scheme for study

We retrieved patient CT/MRI images and structures (contours of the targets and organs at risk), from the treatment plans of previously treated patients. These patients were treated at The James Cancer Hospital at The Ohio State University between 2000 and 2016. For those patients previously treated with LINAC-based SRS, images and structures were acquired through the patient database Eclipse. Within the Eclipse system, plans would have been created through the External Beam Planning section of the program. CT images, contours, and structures were transferred to the Gamma Knife LGP system by first selecting which structures were desired. This was performed by copying structures and plans such as organs at risk (such as the optic nerves, optic chiasm, brain stem, cochlea, etc.), the brain, the lens, and the GTV treatment plans. This was followed by pasting this into a new structure set, with an appropriate labeled that helped distinguish which structure set was desired for the comparison. The plan and structures were sent from the program VelocityAI to the Gamma Knife LGP system through the DICOM (Digital Imaging and Communication in Medicine) grid and was received in the DICOM inbox on the Gamma Knife software.

Once received in the DICOM inbox as part of the Gamma Knife LGP system, the contours and structures were imported to create a new GK plan. After created the plan, the skull must be defined, and this was accomplished by going to “skull definition-images” under the Plan tab and shaping out the skull for every image slide from the CT. Once the skull was defined, the simulated treatment plan dose was calculated by placing shots of radiation on the target until the coverage was 100% or 99%. The shots that were placed were of varying sizes including 4 mm, 8 mm, and 16 mm, which correspond to the different collimator sizes. A higher selectivity of these shots leads to a more efficient treatment as well, where less healthy tissue is receiving doses of radiation. The dose was calculated at 50% of the dose that was given to the patient during LINAC treatment. These plans that were created were using the TMR10 plan. Once the dose was calculated, the plan was then copied using the LGP system and copied into a new plan, this plan with the new dose algorithm Convolution. The Convolution plan factors an inhomogeneous correction where bone is calculated as bone and brain tissue as brain tissue, which is different from the TMR10 plan where everything was considered water. Both the TMR10 plan and the Convolution plan were transferred from the LGP system to the Eclipse program for LINAC by way of the “kpacs” server.

For those patients previously treated with Gamma Knife, images and structures were acquired through the Gamma Knife LGP system. These images and structures were transferred from the LGP system to the Eclipse system for LINAC-based SRS through the "kpacs" imaging server. They were then imported using the "importing wizard" function within Eclipse and a new external beam radiation therapy (EBRT) plan was created. Once created, the "body", which could also be understood as the outline of the skull, needed to be contoured using the contouring tool found under the Treatment Planning QuickLink of Eclipse. The skull contour was defined by using the CT images. Once the skull was contoured, the treatment plan could start to be calculated in the External Beam Planning section of the program under the Eclipse Treatment Planning System. The dose used for this simulated treatment of LINAC-based SRS was displayed using the 100% isodose when compared to the 50% dose of the GK treatment. The actual dose is calculated based on photons in the radiation beam interacting with tissues. The LGP system denotes the dose in Gray (Gy) while the Eclipse system denotes the dose in centiGray (cGy). Using a single field, where the geometry of the field could be changed based on the size of the tumor, and a multi-leaf collimator, a dose algorithm was calculated for the LINAC-based treatment.

Once both the GK and LINAC plans were finished and dose was calculated, they could be compared. One way they were compared is visually but observing the plans side by side to see the dose coverage to tumors and healthy tissues indicating with the isodose lines in relationship to one another. Visually comparing them was accomplished by using a photo snipping tool to obtain a photo of the plans and looking at the two plans side-by-side. A second way the plans were compared was quantitatively by dose-volume histograms (DVHs). DVH is an important quantified figure commonly used in radiation therapy to evaluate the quality of a treatment plan, which indicates how much volume of an organ is receiving how much radiation dose. Using the Eclipse program, a comparison histogram was made using "Create Plan Comparison DVH" under the Planning tab. While making the histogram, one could select the GK TMR10 plan, the GK Convolution plan, or the LINAC plan (EBRT). Therefore, comparisons between the TMR10 and Convolution plans can be made in addition to between the LINAC and GK modalities. The Convolution plan from GK is used to directly compare GK with LINAC because the inhomogeneous correction factor allows for this comparison. Looking at the volume of target affected for the tumor and critical structures at specific doses of radiation for each of the modalities tells us which type of radiation is better for that specific individual.

IV. Results

Visual examination and quantization of dose-volume histogram values were used to compare the effects of GK and LINAC treatment on the target volume and critical structures. There were 51 patients analyzed in this study, each patient having either a single metastatic tumor, an acoustic schwannoma, or a pituitary adenoma. Every patient received either GK radiation therapy or LINAC-based radiation therapy at The James Cancer Hospital at The Ohio State University between 2000 and 2016. The types of results obtained included visual representations of treatment plan overlap, overlapping dose-volume histograms of TMR10 and Convolution plans for target volumes and critical structures, and overlapping dose-volume histograms of Convolution and EBRT plans for target volumes and critical structures. From the dose-volume histograms, tables were created displaying the dose of radiation delivered to varying percentages to a selected volume for both the GK and LINAC modality. Results from three patients in this study, each representing one of the disease types, are shown below.

A. Patient 1

Patient 1 is a pituitary adenoma patient and was previously treated with GK radiation treatment. Treatment was simulated for LINAC-based radiation therapy.

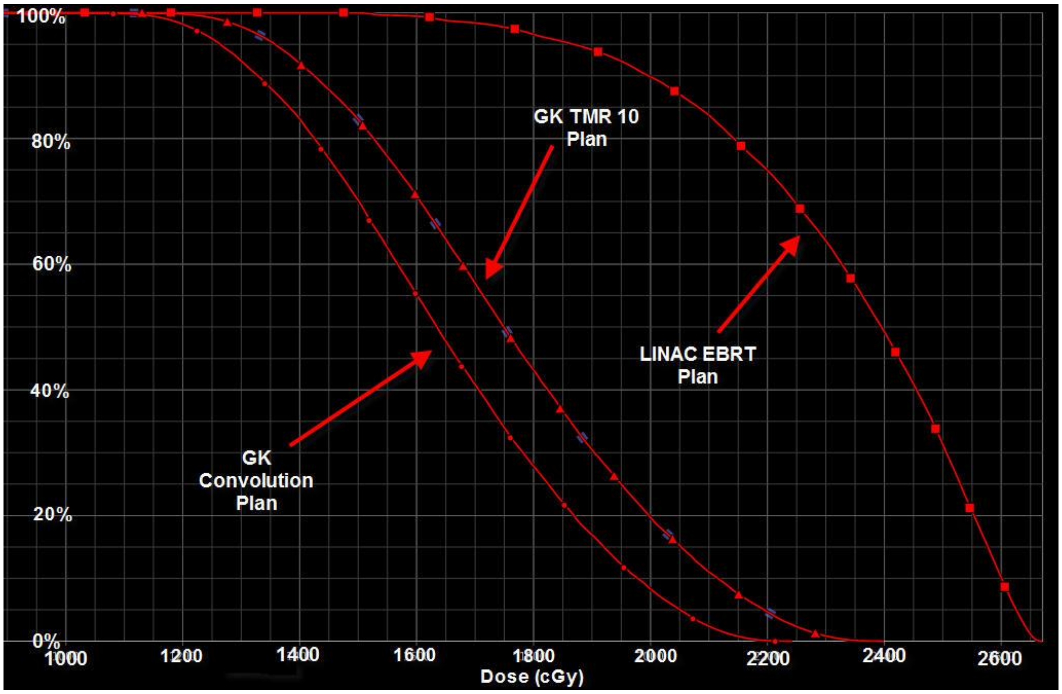


Figure 9:

Comparison dose-volume histogram for patient 1, comparing GK TMR10 plan, GK Convolution plan, and LINAC EBRT plan for the dose exposure on the tumor, a pituitary adenoma.

	Patient 1 on Tumor		
Percent volume coverage	GK TMR10	GK Convolution	LINCAC (EBRT)
Prescribed	22.43	22.43	22.43
90	14.26	13.27	19.94
50	17.48	16.34	23.95
20	19.96	18.69	25.52
2	22.59	21.09	26.42

Table 1:

Table summary of dose exposure to the pituitary adenoma, the target structure, of patient 1 at various percent coverages of total volume. Dose exposure was determined at 90, 50, 20, and 2 percent of total structure volume. All calculated doses are given in Gray (Gy).

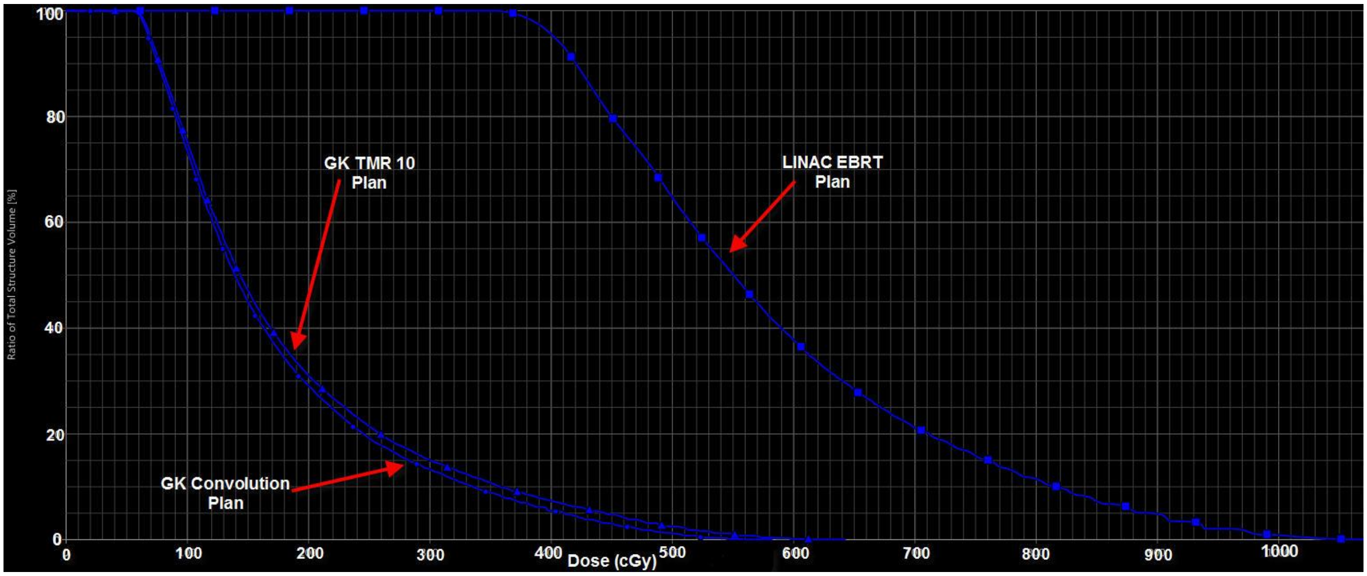


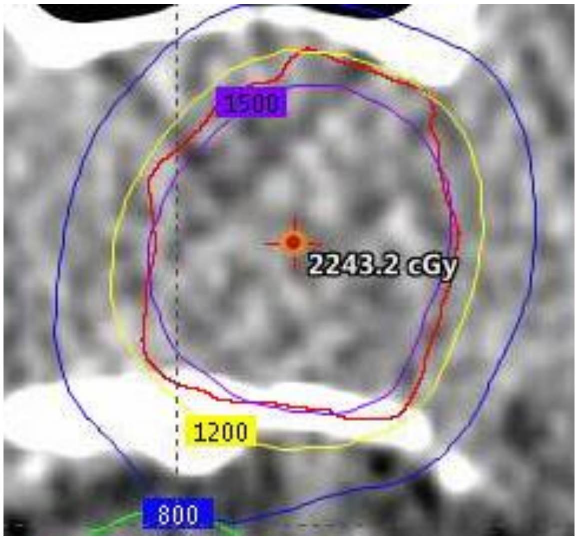
Figure 10:

Comparison dose-volume histogram for patient 1, comparing GK TMR10 plan, GK Convolution plan, and LINAC EBRT plan for the dose exposure on the left optic nerve.

(Coverage %)	GK TMR10	GK Convolution	LINCAC (EBRT)
90	0.77	0.75	4.2
50	1.44	1.42	5.49
20	2.57	2.44	7.07
2	5.11	4.72	9.42

Table 2:

Table summary of dose exposure to the left optic nerve, a critical structure, of patient 1 at various percent coverages of total volume. Dose exposure was determined at 90, 50, 20, and 2 percent of total structure volume. All calculated doses are given in Gray (Gy).



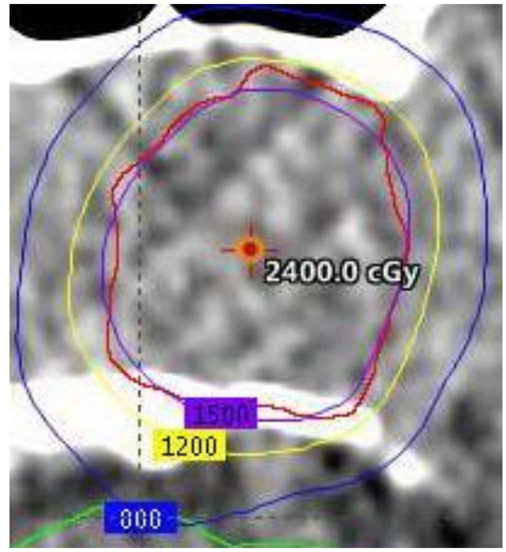


Figure 11:

Planned treatment dose isobars for treatment of the pituitary adenoma for patient 1. The left image is that of the Convolution plan within the GK modality while the right figure is that of the TMR10 plan within the GK modality. The 1500, 1200, and 800 cGy isodoses are marked and the unmarked, outer red line is the tumor.

For patient 1, the lesion type was a pituitary adenoma, which is a benign, slow-growing tumor that arises from cells in the pituitary gland. In figure 9, the DVH for patient 1 shows the dose distribution to the target structure, a pituitary adenoma. The decreasing slopes of both the Convolution and TMR10 plans of the GK modality are rather steep, which is beneficial because it means less healthy tissue is being exposed to harmful amounts of radiation. The Convolution plan requires less dose compared to that of the TMR10 plan however. The decreasing slope of the EBRT is not very steep, mean that more healthy tissue will receive higher doses of radiation, which is not desired. This plan also requires a higher dose compared to the GK modality plans, so visually the Convolution plan appears to be the most effective way of the treating the pituitary adenoma.

Statistical results seen in table 1 give us more insight about this claim. For 50% volume of the target structure, the dose received will be 17.48 Gy and 16.34 Gy for the Convolution and TMR10 plans, respectively. The dose for the EBRT plan at the same volume, however, is 23.95 Gy. Also, the dose delivered to 2% volume of the target structure using the TMR10, Convolution, and EBRT plans were 22.59 Gy, 21.09 Gy, and 26.42 Gy, respectively. This tells us that much more radiation is required by the LINAC EBRT plan to treat the same tumor compared to the GK modality plans, which is unnecessary from a dosimetry and physics standpoint alone.

Seen in figure 10 is the DVH for the radiation treatment affecting a critical structure, the left optic nerve of patient 1. Visual examination of the DVHs, comparing the Convolution, TMR10, and EBRT plans, shows us that none of the plans have a decreasing slope of dose that is very steep, which would mean that more radiation would be delivered to healthy tissue than what might been desired. The Convolution plan indicates the lowest dose to the exposed to this critical structure, however, followed by the TMR10 plan and then the EBRT plan. This can be expressed quantitatively using the data provided in table 2. For 90% volume of the total critical structure, 0.77 Gy and 0.75 Gy would be delivered to the left optic nerve by the TMR10 and Convolution plans, respectively. The EBRT plan would deliver 4.2 Gy to the same volume of critical structure though, which is a much higher dose and much less desired. From the results obtained, it was be stated that the Convolution plan of the GK modality provided the most effective treatment of the pituitary adenoma for patient 1.

B. Patient 2

Patient 2 is an acoustic schwannoma patient and was previously treated with GK radiation treatment. Treatment was simulated for LINAC-based radiation therapy.

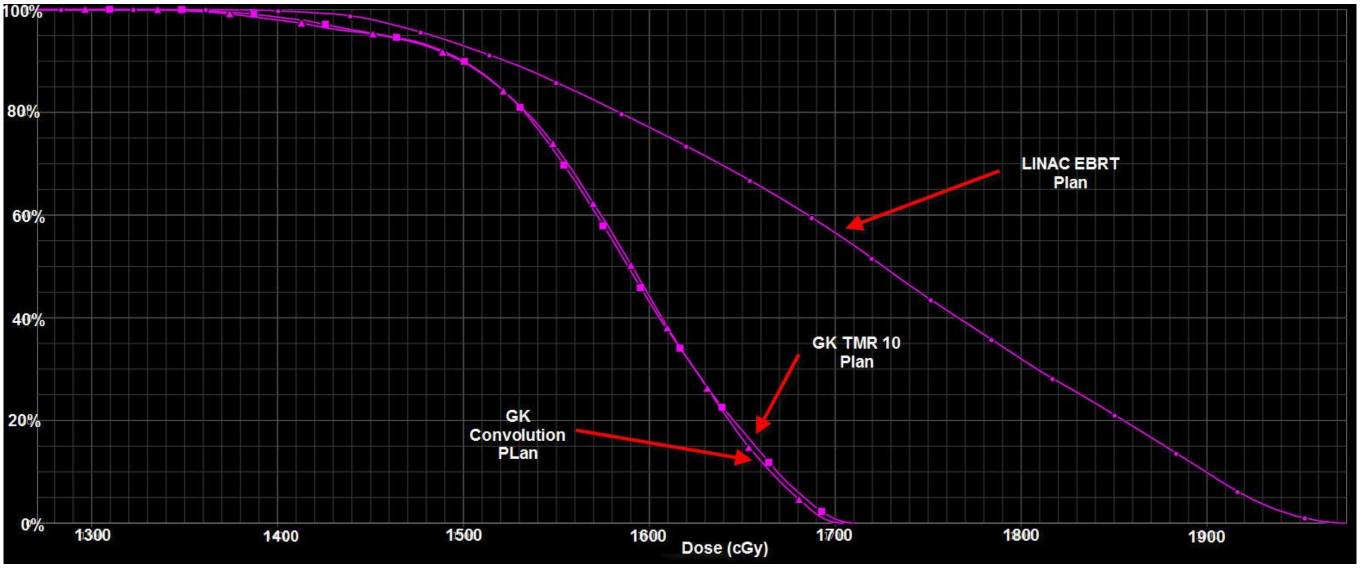


Figure 12:

Comparison dose-volume histogram for patient 2, comparing GK Convolution plan, GK TMR 10 plan, and LINAC EBRT plan for the dose exposure on the tumor, an acoustic schwannoma.

	Patient 2 on Tumor		
Percent volume coverage	GK TMR10	GK Convolution	LINCAC (EBRT)
Prescribed	17.14	17.14	17.14
90	14.98	14.98	15.23
50	15.88	15.91	17.26
20	16.45	16.42	18.55
2	16.93	16.89	19.42

Table 3:

Table summary of dose exposure to the acoustic schwannoma, the target structure, of patient 2 at various percent coverages of total volume. Dose exposure was determined at 90, 50, 20, and 2 percent of total structure volume. All calculated doses are given in Gray (Gy).

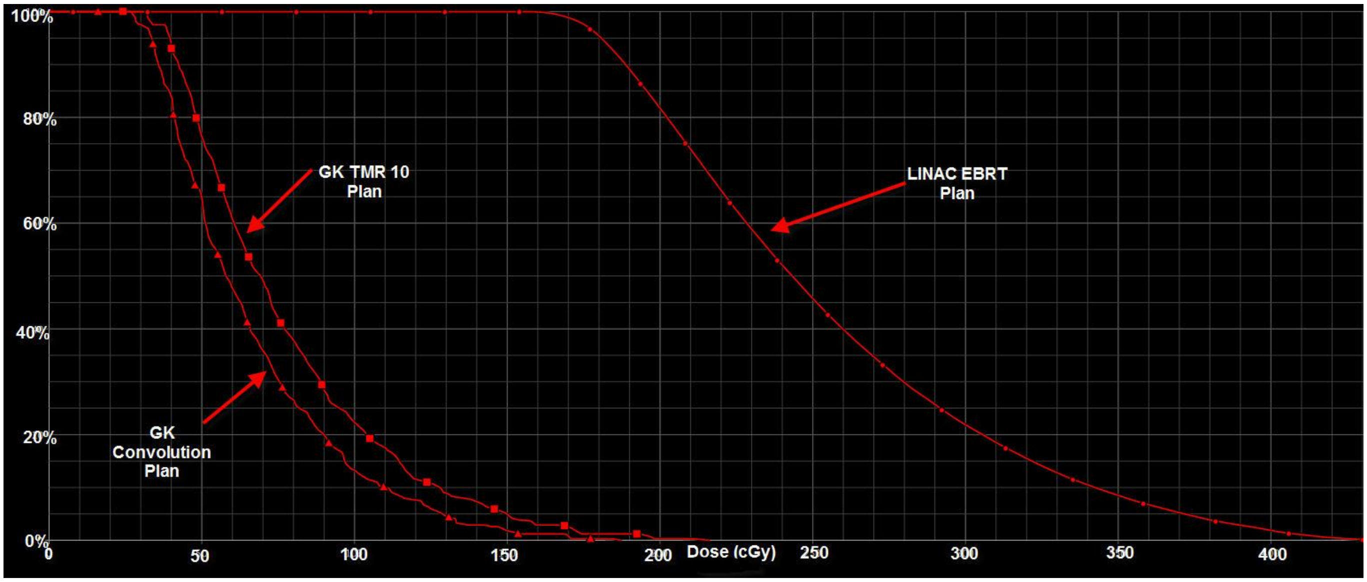


Figure 13:

Comparison dose-volume histogram for patient 2, comparing GK Convolution plan, GK TMR10 plan, and LINAC EBRT for the dose exposure on the right cochlea.

(Coverage %)	GK TMR10	GK Convolution	LINCAC (EBRT)
90	0.42	0.35	1.88
50	0.69	0.58	2.43
20	1.03	0.91	3.06
2	1.71	1.49	3.98

Table 4:

Table summary of dose exposure to the right cochlea, a critical structure, of patient 2 at various percent coverages of total volume. Dose exposure was determined at 90, 50, 20, and 2 percent of total structure volume. All calculated doses are given in Gray (Gy).

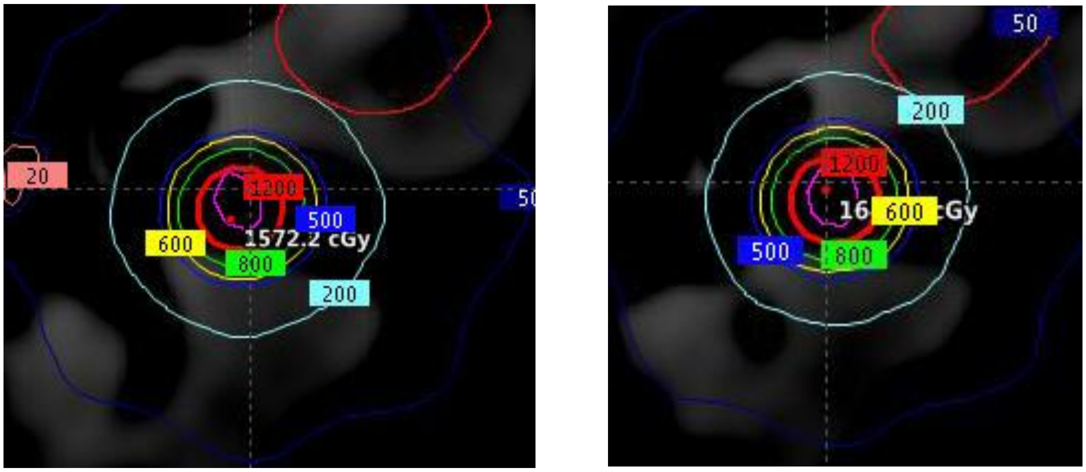


Figure 14:

Planned treatment dose isobars for treatment of the acoustic schwannoma for patient 2. The left image is that of the Convolution plan within the GK modality while the right figure is that of the TMR10 plan within the GK modality. Various isobars, given in cGy, are marked with the bold red isobar being the 100% dose and the pink structure being the tumor.

Patient 2 had a type of tumor called an acoustic schwannoma, also called a vestibular schwannoma. A vestibular schwannoma is a benign, usually slow-growing tumor that develops from the balance and hearing nerves supplying the inner ear. Overproduction of Schwann cells leads to the tumor formation (NIH, 2017). The planned treatment for patient 2 was analyzed based on its effective dose delivered to both the tumor and the critical structures. The DVH for the plans affecting the target structure, the acoustic schwannoma, are seen in figure 12. The TMR10 and Convolution plans are very similar when considering dose distribution while the EBRT plan requires a higher dose. There is a noticeable discrepancy between the plans with and without the correction for inhomogeneity because this type of tumor is found near the ear, where many small bones exist. The decrease in the dose delivered is not as sharp for the EBRT plan as the GK modality plans. Quantitatively described in table 3, at 90% volume coverage evaluated, 14.98 Gy was delivered by both the TMR10 and Convolution plans while the EBRT plan delivered 15.23 Gy to that volume of the target. Also, at 50% volume, the difference in dose between the Convolution and EBRT plans was 15.91 Gy versus 17.26 Gy, respectively.

In this case, the critical structure was the right cochlea and the DVH for the radiation effect on this critical structure can be seen in figures 13. It can be seen visually that the Convolution plan and EBRT plan are somewhat similar, with the Convolution plan the critical structure receives the lower dose. For Convolution plan, the right cochlea receives less dose than the TMR 10 plan. This is most likely due to the inhomogeneous factor used in that specific dose algorithm calculation and the bones around the cochlea attenuate some radiation. In the EBRT plan, a higher dose is received by the tumor and the decrease in dose per area as seen in the DVH is not steep, which is not as effect as the GK modalities. Numerically seen in table 4, 50% volume of structure is being exposed to 0.69 Gy and 0.58 Gy for TMR10 and Convolution plans, respectively, while at this same percent coverage, 2.43 Gy of radiation would be delivered using EBRT. Based on the visual and quantitative data, it can be said that the Convolution plan of the GK modality provides the most effective treatment of the acoustic schwannoma in the case of patient 2.

C. Patient 3

Patient 3 is a single-metastatic tumor patient who was previously treated with GK. Treatment was simulated for LINAC-based radiation therapy.

A B C

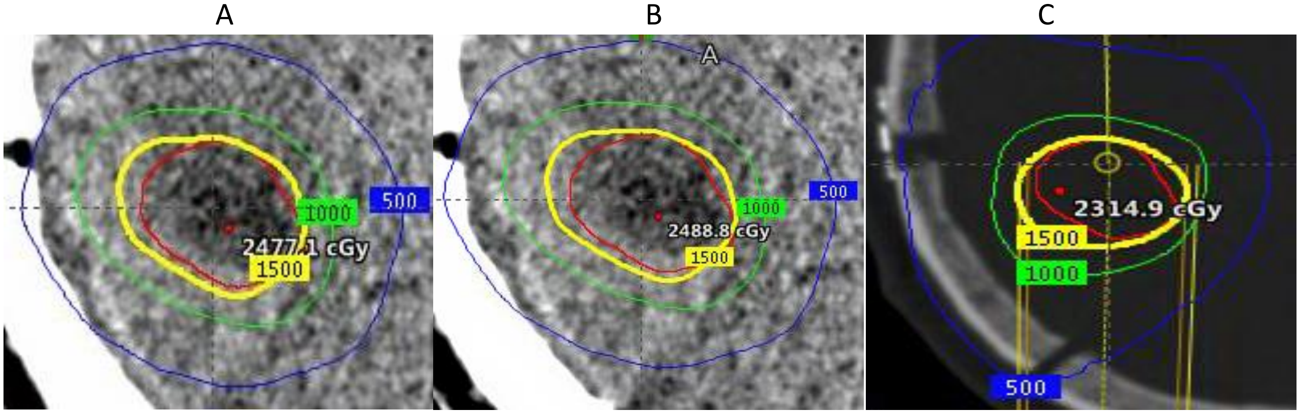


Figure 15:

Planned treatment dose isobars for treatment of the single metastatic tumor for patient 3. Image A is that of the Convolution plan within the GK modality, image B is that of the TMR10 plan within the GK modality, and image C is that of the EBRT plan of the LINAC modality. The 1500, 1000, and 500 cGy isodoses are shown and the red structure is the metastasis.

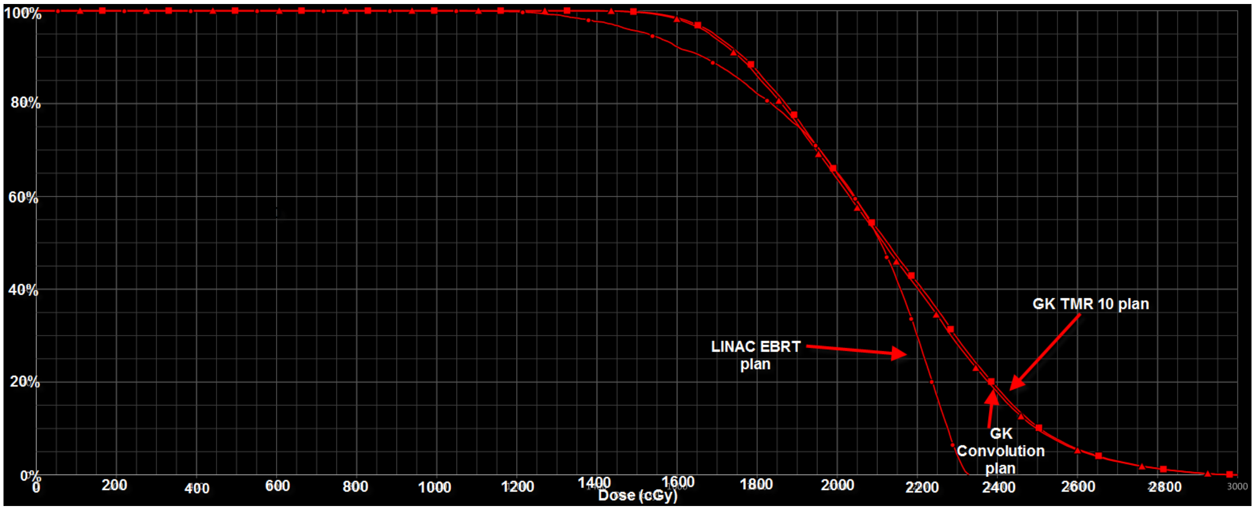


Figure 16:

Comparison dose-volume histogram for patient 3, comparing GK Convolution plan, GK TMR 10 plan, and LINAC EBRT plan for the dose exposure on the tumor, a single metastatic tumor.

	Patient 3 on Tumor		
Percent volume coverage	GK TMR10	GK Convolution	LINCAC (EBRT)
Prescribed	15	15	15
90	17.64	17.56	16.68
50	21.26	21.15	21.07
20	23.86	23.76	22.38
2	27.45	27.45	23.11

Table 5:

Table summary of dose exposure to the single metastatic tumor, the target structure, of patient 3 at various percent coverages of total volume. Dose exposure was determined at 90, 50, 20, and 2 percent of total structure volume. All calculated doses are given in Gray (Gy).

Patient 3 has a type of tumor called a single metastatic tumor. A metastatic brain tumor is cancer that started in another part of the body and has spread to the brain. As seen in figure 15, the plans for treatment on this tumor are different across the two modalities and the two plans within the GK modality. The specificity and coverage are very similar for the Convolution and TMR10 plans by visual examination, but this cannot be said for the EBRT plan in image C. The coverage and specificity for this EBRT plan is not as high, leading to the claim that this plan is not the most effective from a visual analysis perspective. Viewing the DVH in figure 16, one could observe that the dose distribution for the Convolution and TMR10 plans are very comparable with this statement being supported by numerical data found in table 5. At all the intermediate volume levels evaluated, the calculated dose between the two plans was only separated by at most 0.11 Gy, meaning that the two plans are very comparable, with the Convolution plan having the slightly lower dose requirement.

In comparison of the Convolution plan with the EBRT plan using figure 16 and table 5, it was seen that both the Convolution plan and the EBRT plan gives similar radiation dose to the tumor, which is opposite of what was seen in many other cases for the other two lesion types and for other single metastatic tumors. The decrease in dose outside of the target structure is much steeper for EBRT than Convolution as well. Quantitatively, 90% volume of target receives at least 17.56 Gy for the Convolution plan and 13.69 Gy for the EBRT plan, while at 20% volume these values are 23.76 Gy and 17.02 Gy, respectively. From the visual and quantitative analysis of treatment plans for patient 3, it appears that the LINAC EBRT plan would provide the most effect treatment of the single metastatic tumor. However, in this case, both plans have to be evaluated by comparing the doses to the critical structures which is not shown here.

V. Discussion

The results of this study can have an impact on the process by which oncologist determine the most effective means of treatment for cancer patients. However, while the process of determine the best course of action involves the physics and dosimetry analyzed in this study, physicians use many others factors as well to determine which treatment modality is better for a patient besides considering the dosimetry factor that we study here, which is generally the most important one among all the factors. An abbreviated list of factors that the physicians use to make these decisions include age, sex, previous surgical history, family history, sensitivity to treatment, and patient wishes or preferences. There is no generic case of cancer and everyone's unique circumstances are considered when creating a plan of treatment.

Evaluation and analysis of the represented patient results and the results of all individuals in the study allow us to make claims about the effectiveness between the LINAC-based radiation therapy and GK radiation therapy and between the GK Convolution dose algorithm and GK TMR10 dose algorithm. It was found that in the majority of cases, across all lesion types, the tumor coverage and specificity for the tumor was greatest for the GK modality using the Convolution plan. There were some occurrences, however, where the EBRT plan from the LINAC modality had the most effective treatment plan for the patient. An example of this was patient 3 discussed earlier in the paper. It was also found, that in almost all cases, the Convolution plan was more accurate to describe the reality of treating the tumor than the TMR 10 plan as it takes into account the inhomogeneity correction for tissues, both within the GK modality. This is believed to be based on the utilization of the inhomogeneous factor in the dose calculation algorithm. The difference in the effectiveness between the GK and LINAC modalities could stem from the lack of accuracy for the calculation for LINAC. This inaccuracy is due to the inability to have complete immobilization during treatment, so a larger margin of error when designing the treatment plan is employed. The energy delivered using the LINAC is often much greater than the GK plans, so the probability of radiation being exposed to normal tissue surrounding the tumor is greater. Avoiding this effect is a goal of every treatment, meaning more focused plans that solely radiate the tumor are the most desirable, because exposing organs to certain amounts of radiation could have negative physiological effects.

The effectiveness of treatment in this study was not only based on the coverage and selectivity of the planned dose algorithm on the tumor, but also the plans decrease in dose exposure has distance from the isocenter of the tumor increased. By having a significant decrease in dose exposure on tissue outside of the target structure ensures that the radiation does not harm healthy tissue. Not only could healthy brain tissue be affected if the dose of radiation was still too strong, but also critical structures and organs such as the brain stem and optic nerve could be impacted which could lead to physiological impairments.

The study performed and the results obtained from this study can lead to other inquiries and further research in the field of study and related fields of study. In this study, the treatment modalities and plans within those modalities for treatment of tumors was compared. Different dosimetry studies could be performed, however, evaluating the effects of having tumors at different locations within the skull and having tumors closer or farther from certain critical structures. This can also lead to significant results, as in the study we performed, it was observed that the treatment plans were much more difficult to create and dose calculation values were different for those cases where the tumor was close to some or many critical structures.

The results of this study can also lead to further research outside of the world of radiation oncology, dosimetry, and physics. For example, this study could be applied to the worlds of biology and molecular genetics. The genetic makeup of the individuals in the study could be analyzed, looking for certain genes or biomarkers. If there is a high rate of correlation between the presence of a certain gene or biomarker and a certain tumor, one could then look at the effectiveness of each modality on the treatment of that tumor. A pattern seen in relating the most effective treatment modality for the certain biomarker and tumor location could give radiation oncologist and other health professionals insight on which treatment can most effectively treating certain tumors without simulating both treatment modalities using computer programming. If this study was found to be successful, the discovery of a biomarker relating to a tumor that is almost always more effectively treated with GK could give the physician a progressive insight when planning treatment for the patient. In general, the results gathered in this study could serve a major stepping stone in other areas of medicine and cancer treatment.

VI. Conclusion

After obtaining results from this project, it was observed that the GK and LINAC methodologies have their own advantages and disadvantages when treating lesions, which may vary depending on location of tumor or disease type. Neither of the modalities were better than the other in all or most cases, and there were no identical plans between GK and LINAC for each individual patient. There was a higher specificity for tumor coverage for the GK modality compared to the LINAC modality in most cases however. There was also a notable difference between the TMR10 and Convolution plans within the GK modality due to the inhomogeneous correction factor being incorporated in the Convolution plan while not being used in the TMR10 plan. The proper treatment modality for individual patients may require the consideration of other factors then the dosimetry alone, which is worth further investigation.

VI. References and Acknowledgements

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